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14. ABSTRACT

In the PECASE program, we address another challenge of small-scale flight: energetics. Gliding forward flight potentially alleviates both of these challenges since gliding requires minimal power and forward flight can achieve passive stability (e.g. using a positive wing dihedral). Many insects effectively use gliding modes to extend flight duration – for example, Monarch butterflies travel greater than 50 miles per day during migration and thousands of miles in aggregate. The PECASE program elucidated generate energy-optimal strategies for flapping/gliding intermittent flight through the development of a robotic insect capable of bio-inspired flapping/gliding flight and a thorough characterization of the energetics of this flight mode. The overall objective is to elucidate the role of intermittent flight in biology and apply this to increase the performance of insect-scale MAVs.

15. SUBJECT TERMS

micro air vehicles, bioinspired flight, bioinspired robotics

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Re: Closeout Documentation for Grant No. N00014-10-1-0684 (Professor Rob Wood)

To Whom It May Concern:

Enclosed please find one hard copy of the Final Technical Report with SF298 for Professor Robert Wood's grant no. N00014-10-1-0684.

Please contact me with any questions.

Thank you,

EDBrady

PI Name: Robert Wood
Organization: School of Engineering and Applied Sciences, Harvard University
ONR Award Number: N00014-10-1-0684
Award Title: "PECASE: Soaring mechanisms for flapping-wing micro air vehicles"
(previous award: N00014-08-1-0919, "Hovering Control for Insect-Inspired Flapping-Wing Micro Air Vehicles")

Final report

a. Scientific and Technical Objectives

The Harvard Microrobotics Lab has demonstrated the smallest flapping-wing devices to date which can generate thrust greater than their body weight. Due to size and weight constraints, these devices exacerbate challenges of power and control for autonomous MAVs. The initial YIP award explored control techniques - both in terms of the physical and controller designs - for insect-scale vehicles in hover. Hovering turns out to be a challenging flight mode given the lack of passive stability mechanisms. Furthermore, robots at the scale of insects must be developed from scratch since there are very few commercially available components that would satisfy the strict size, weight, and power limitations of this platform. In the PECASE program, we address another challenge of small-scale flight: energetics. Gliding forward flight potentially alleviates both of these challenges since gliding requires minimal power and forward flight can achieve passive stability (e.g. using a positive wing dihedral). Many insects effectively use gliding modes to extend flight duration – for example, Monarch butterflies travel greater than 50 miles per day during migration and thousands of miles in aggregate. The PECASE program elucidated generate energy-optimal strategies for flapping/gliding intermittent flight through the development of a robotic insect capable of bio-inspired flapping/gliding flight and a thorough characterization of the energetics of this flight mode. The overall objective is to elucidate the role of intermittent flight in biology and apply this to increase the performance of insect-scale MAVs.

b. Approach

Our approach for both programs was highly experimental - we leverage our unique meso/micro-scale manufacturing methods to create flying robots on the scale of insects and with comparable flight characteristics. We then use these robots to study controls and energetics for insect-scale flight. This is a major advantage to our approach: previous research on understanding insect flight has focused on biology studies - which are hard to control - or dynamically-scaled models or simulations. Our ability to make flying robots allows us to directly experiment with both morphology, energetics, and control.

c. Concise Accomplishments

In the YIP program we demonstrated the first controlled flight of an insect-scale robot (see Fig. 1). Leveraging these results (specifically, the manufacturing methods used to create that vehicle), in the PECASE program we have developed the first insect-scale vehicle capable of free-flight for intermittent flight experiments. This is the culmination of efforts to design, and integrate all the constituent components (i.e. wings, transmission, airfoils, controller, airframe, motor, and batteries). We have also developed detailed models and simulations that are complimented by our flight experiments. Using this vehicle we performed the first free-flight IF demonstrations along with preliminary analysis of cost-of-transport (COT) for intermittent flight as a function of IF duty cycle.

Fig. 1: The first controlled flight of an insect-scale robot.

d. Expanded Accomplishments

Our YIP program concluded with the first demonstrations of controlled flight for an insect-scale robot. This was a synergy of breakthroughs in microfabrication and control for under actuated systems. This was published in a highly publicized article in the journal *Science* in 2012. Subsequently, these results have been expanded on in other programs to include controlled maneuvers, takeoff/landing, and perching. This will continue to be a fish research platform for several years as we explore the integration of sensors, computation, and power in order to achieve untethered flight.

Our PECASE program addressed one of the biggest challenges with micro air vehicles: the energetic intensity of flight at small scales and energy density limitations of available power sources. Gliding requires an absolute minimum of power, however there are multiple challenges in attaining effective gliding for MAVs. In particular, MAVs typically live in a viscous-dominated low Reynolds number flow regime. In this fluid regime, the ratio of lift-to-drag coefficients is typically low (e.g. less than 10) due to the dominance of viscous drag and detached flow. However, certain insects successfully utilize gliding modes and in this work we seek to elucidate the structures which enable this – not only the aeromechanical components, but also the flapping mechanics and control which will choose to switch between flapping propulsion and passive flight - which we collectively define as *intermittent flight*.

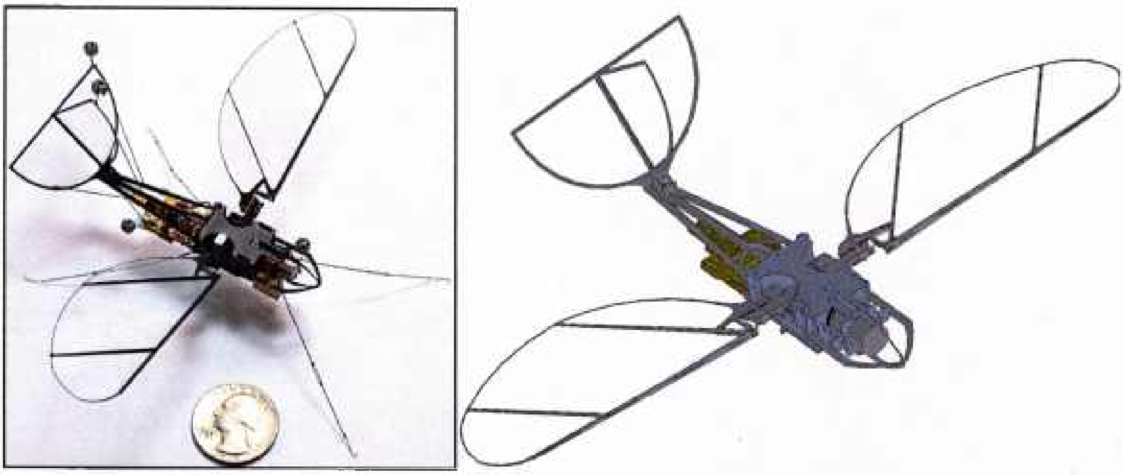

Fig. 2: Completed intermittent flight vehicle. This MAV weighs approximately 2.8g and has the ability to perform free-flight with a programmable duty cycle of active to passive flight duration.

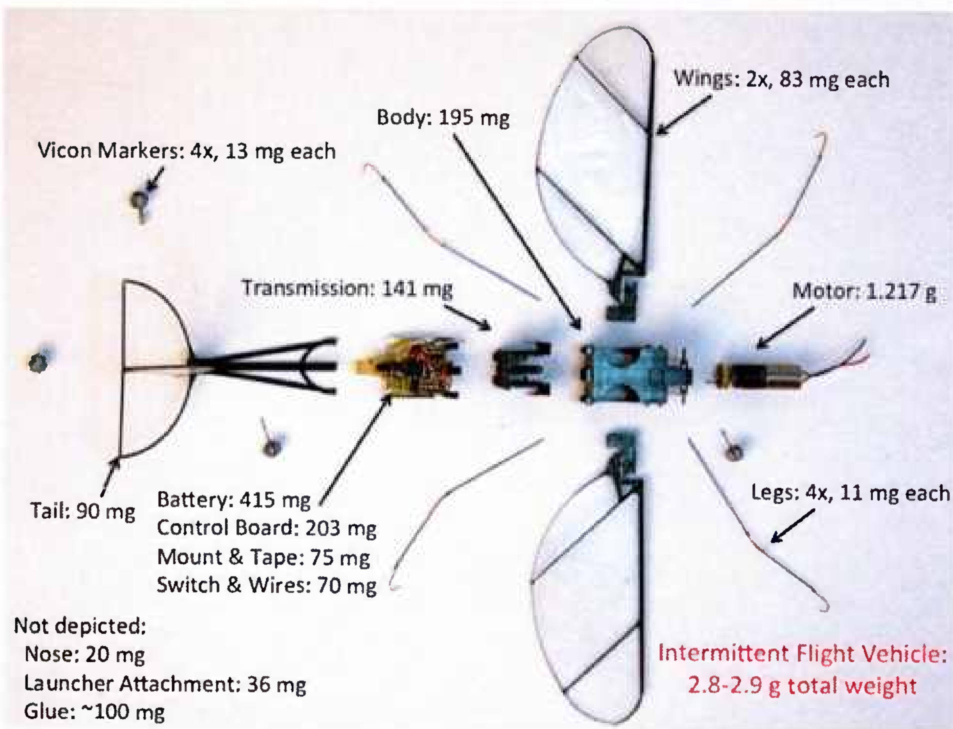

Fig. 3. Illustration of the components that make up the IF vehicle. The vast majority of these are custom with the exception of the motor and gear box, battery, and the discrete components that make up the power/control board.

To study the energetics of intermittent flight, we have constructed a MAV roughly on the size of insects and small birds that display this flight pattern. This vehicle, shown in Fig. 2, has a wing span of approximately 15cm and a mass of 2.8 grams. This consists of an off-the-shelf DC motor (with gearhead), and custom components made using our advanced meso-scale manufacturing methods based on lamination and folding of high-performance composites. Each of the constituent components are highlighted in Fig. 3. Prior to flight tests, these MAVs are thoroughly characterized both in bench-top and wind tunnel experiments. Static experiments with the MAV mounted to a force/torque sensor demonstrated time-average thrusts that would vary from model to model, but ranged from approximately 1.5 to 2× the total body mass, indicating more than adequate force production for sustained flight. Following bench-top experiments, we also performed wind tunnel experiments to verify thrust production in relevant airspeeds and to also measure body moments as a function of stabilizer angle. Flow visualization was also performed (see Fig. 4) to ensure that other components of the MAV were not producing undesired effects to the surrounding flow. Power measurements as a function of wind speed and body angle were also taken for use in cost-of-transport calculations from free-flight tests (we verified that power consumption on bench-top did not differ from wind tunnel tests by more than a few percent).

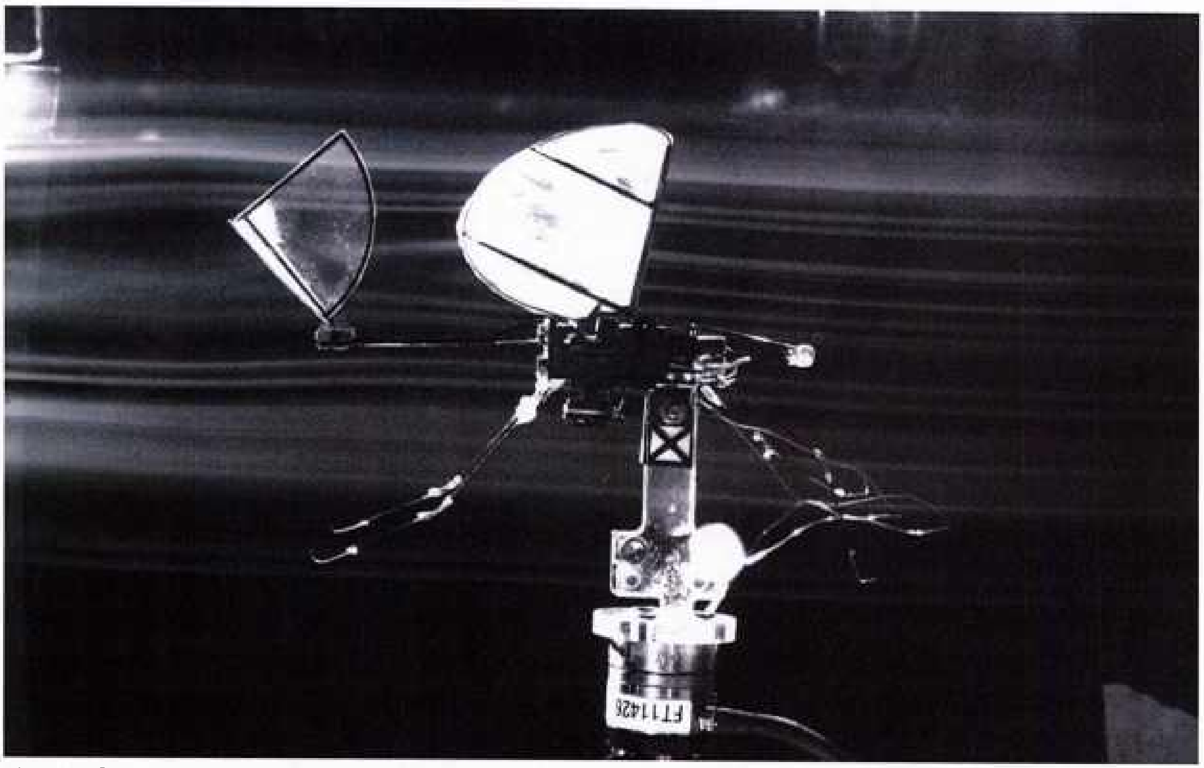

Fig. 4: Photo from flow-visualization experiments in a low-speed wind tunnel. We use bench-top and wind-tunnel tests to characterize the performance of the vehicle and inform/validate our simulations.

These bench-top and wind tunnel experiments were also used to inform and validate a model of the MAV for use in flight simulations. We were able to capture the flight dynamics (projected to a 2D plane) relative to our free-flight experiments (Fig. 5). This model was used to assist in the vehicle design and to assist with the choice of initial parameters for the free-flight experiments.

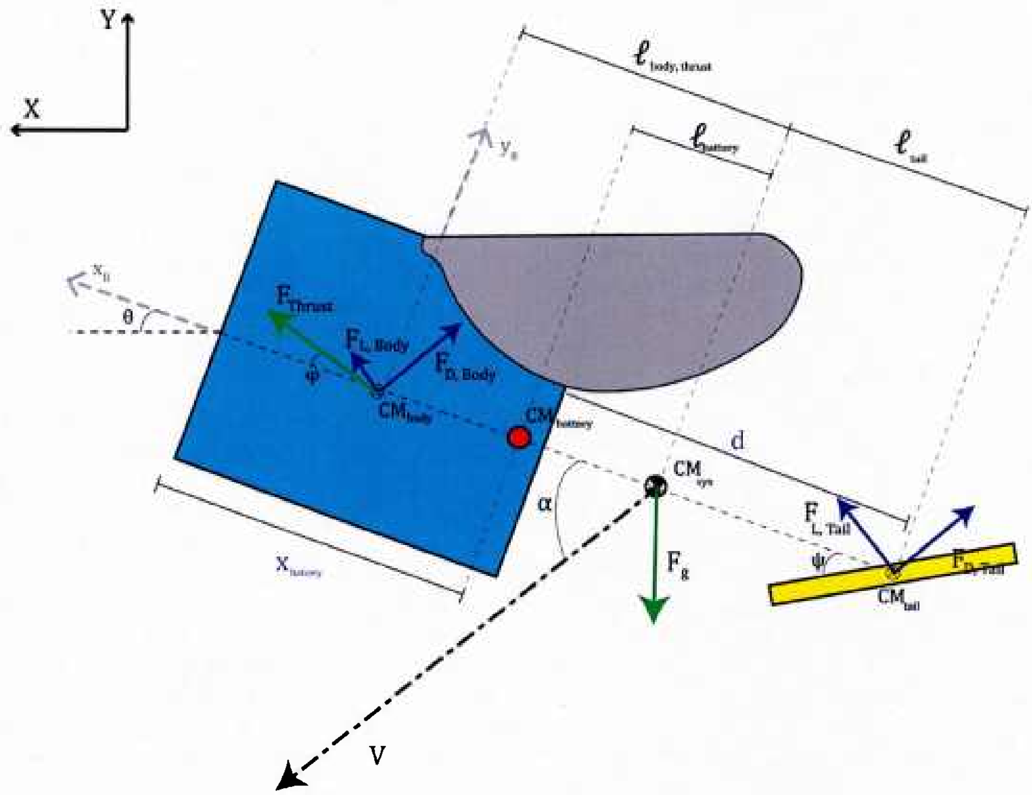

Fig. 5: Example of 2D model of the flight dynamics of the intermittent flight vehicle.

The duty cycle between active flapping and passive gliding was controlled by a custom 200mg control board. The motion capture system, shown in Fig. 6, is used to capture the body state (i.e. position, orientation, velocity, and angular velocity) in real time. A high speed video camera assists with visualization of the flights and to observe wing motion.

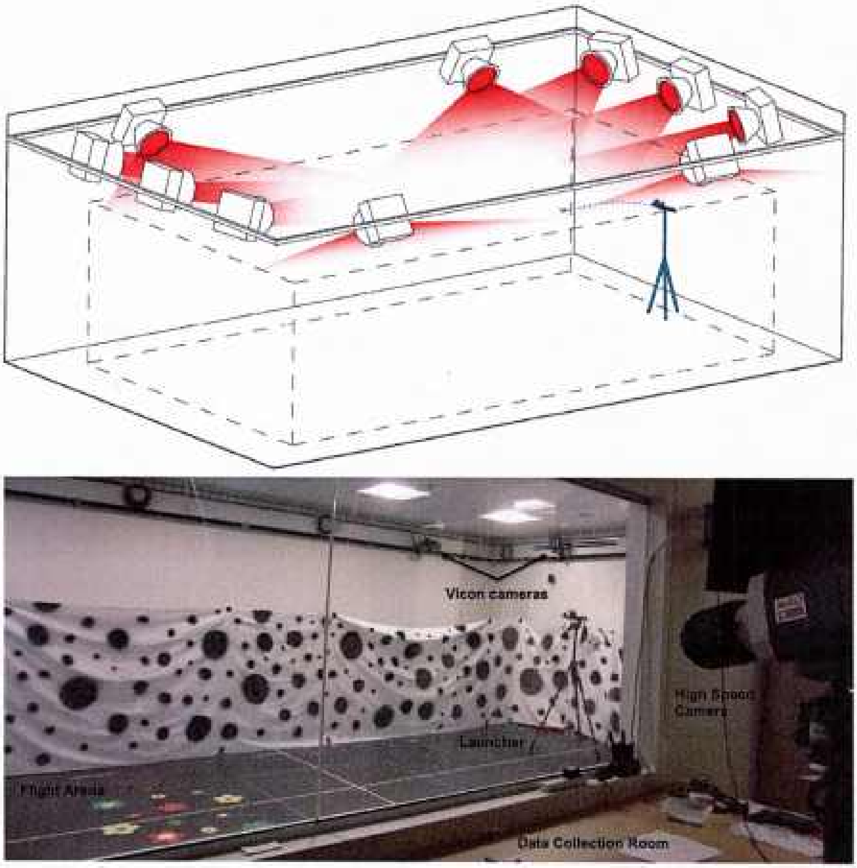

Fig. 6: The flight test arena consists of a set of motion capture cameras (to track passive markers mounted to the MAV), a high-speed video camera, and a custom launcher that ensures consistent initial flight conditions and also triggers the camera and motion capture systems.

Free flight tests were performed in the arena shown in Fig. 6. Despite the thorough simulation and characterization prior to flight, these flights nevertheless required numerous iterations to determine the appropriate trimming required to achieve stable flight. Finally, we performed a set of experiments at IF duty cycles ranging from 0% (i.e. pure gliding) to 100% (i.e. pure active flapping propulsion). We used these to perform an initial analysis of the energetics of flight as a function of duty cycle by calculating cost-of-transport (COT) for each flight (Fig. 7). Note that not all duty cycles can achieve sustained flight for this particular vehicle - below roughly 70%, the average thrust is insufficient to support the weight of the vehicle. Analysis of these COT results suggests that the optimal strategy for intermittent flight is to choose the lowest duty cycle that is still capable of sustained flight.

Ongoing work is currently repeating these experiments, and most importantly, choosing vehicle parameters (i.e., tail angle) to achieve level flight for each duty cycle (each duty cycle capable of sustained flight). This is important since, as shown in Fig. 7, the vehicle ascends or descends during flight. This trimming will allow us to make more accurate comparisons across IF duty cycles. Beyond that, our work will focus in two areas. First, we will hack existing larger (bird-size) flapping-wing MAVs and perform similar experiments to attempt to judge the scaling effects of optimal duty cycle choice. Second, we are currently revising the control board to integrate sensing (i.e., IMU), communication (i.e., to relay sensor information), actuation for control surfaces (e.g., using our expertise in small-scale electromagnetic actuators), and control for autonomous flight stabilization. Beyond the energetics studies of the PECASE program, we are hopeful that this vehicle can serve as a platform for a variety of missions and applications - things ranging from hazardous environment exploration to search and rescue.

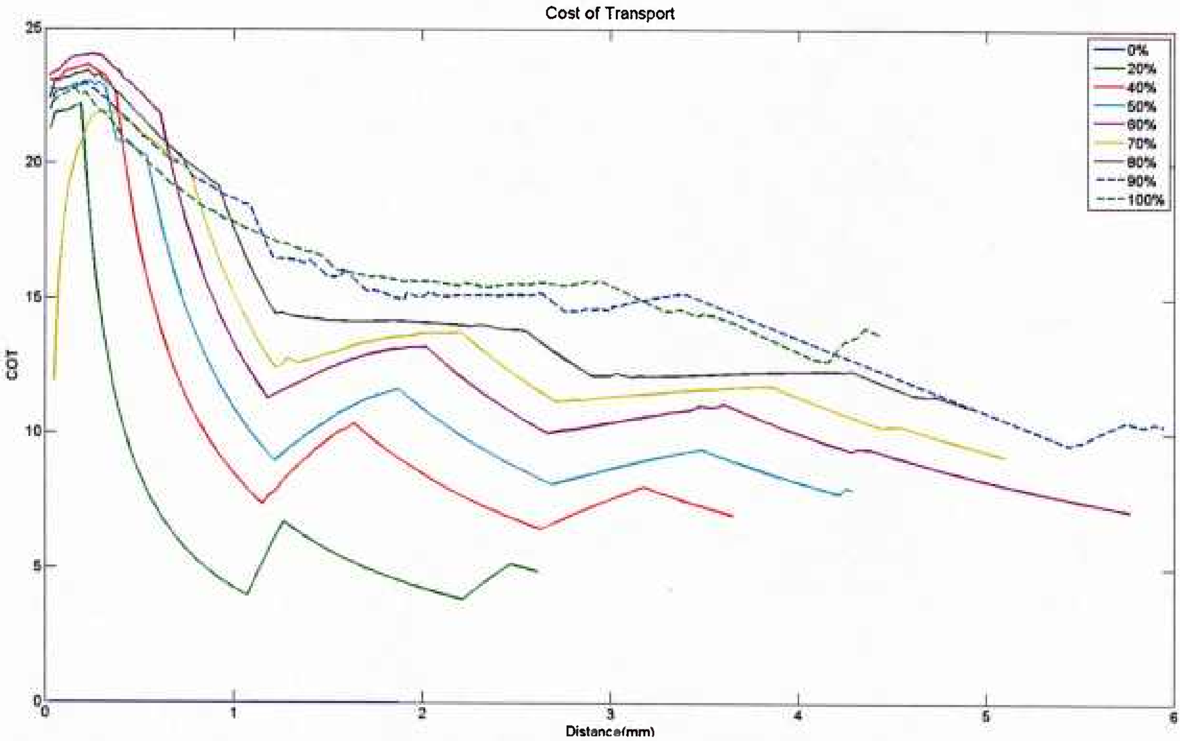

Fig. 7: Example COT plots for preliminary flight trials for various IF duty cycles.

e. Work Plan
NA

f. Major Problems/Issues
No major problems.

g. Technology Transfer
We have recently leveraged the same manufacturing methods used to create the prototypes in these projects to secure a DARPA contract on advanced manufacturing ("Atoms to Products" program), specifically focused on the development of robotic surgical tools.

h. Foreign Collaborations and Supported Foreign Nationals
Dr. Mirko Kovac (PhD, EPFL), Dr. Nestor Perez-Arancibia (Ph.D, UCLA)

i. Productivity

Over the course of the YIP and PECASE programs, there have been multiple papers describing our research accomplishments (including a paper in *Science* describing the first controlled flight of robotic insects). In addition, Wood won several awards including the 2012 NSF Alan T. Waterman award and in 2014 was named one of National Geographic's "Emerging Explorers" for his work in microrobotics that was partially supported by the YIP and PECASE awards.

j. Award Participants
Prof. Robert Wood (PI)
Dr. Ranjana Sahai (postdoc)
Dr. Noah Jafferis (postdoc)
Michelle Rosen (graduate student)
Michael Smith (staff engineer, not supported from this grant)
Pierre-Marie Meyitang (staff engineer, not supported from this grant)
Michael Karpelson (staff engineer, not supported from this grant)